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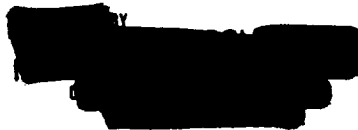
THE SPATIAL RESOLVING POWER OF EARTH RESOURCES SATELLITES: A REVIEW

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16. Abstract <p>The significance of spatial resolving power on the utility of current and future Earth resources satellites is critically discussed and the relative merits of different approaches in defining and estimating spatial resolution are outlined. It is shown that choice of a particular measure of spatial resolution depends strongly on the particular needs of the user. Several experiments have simulated the capabilities of future satellite systems by degradation of aircraft images. Surprisingly, many of these indicated that improvements in resolution may lead to a reduction in the classification accuracy of land cover types using computer-assisted methods. However, where the frequency of boundary pixels is high, the converse relationship is found. Use of imagery dependent upon visual interpretation is likely to benefit more consistently from higher resolutions.</p> <p>Extraction of information from images will depend upon several other factors apart from spatial resolving power: these include characteristics of the terrain being sensed, the image processing methods that are applied as well as certain sensor characteristics.</p>			
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A REVIEW*

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THE SPATIAL RESOLVING POWER OF EARTH RESOURCES SATELLITES: A REVIEW

1. Introduction

Earth resources satellites which are currently being constructed or designed for launching in the 1980's will provide images with substantially better spatial resolution than those commonly available from civilian satellites during the last decade. In the 1970's the very large majority of satellite images of the Earth's surface suitable for the study of terrain properties were obtained from the Landsat series of satellites. Many Earth scientists were quick to exploit the potential of this new source of environmental information (e.g. NASA 1973a; NASA 1975), but others found it wanting. Not least, this was caused by the lack of ground detail which the imagery displays (i.e. its low spatial resolution) compared with that in conventional air photographs.

Operational use of such data has similarly been hindered by their relatively poor resolution. Figure 1 shows the results of a recent survey of the needs of the major U.S. government agencies for remote sensing data in terms of spatial resolution. Given the current resolution of the Landsat MSS of 79m it is clear that the needs of many users are not apparently being met.

These perceived needs for higher resolution imagery will be partially satisfied by the better resolving capabilities of Landsat D scheduled to be launched in 1982 (CORSPERS, 1976; Salomonson, 1978; Salomonson et al. 1980) and of SPOT (Système Probatoire d'Observation de la Terre) to be launched in 1984 (Gaubert, 1978). Other high resolution systems that have been proposed include Mapsat (Colvocoresses, 1979a), Stereosat with sensors looking fore and aft to produce stereoscopic coverage, (Jet Propulsion Laboratory, 1979) a large format camera on Spacelab (Doyle, 1979) and a Synchronous Earth Observation Satellite (Doyle, 1978). Additionally there are classified surveillance systems such as the KH-11 of the U.S. with very high resolving powers, though the resultant imagery is not widely circulated.

**U.S. GOVERNMENT AGENCY USER REQUIREMENTS
FOR SPATIAL RESOLUTION OF REMOTELY SENSED
DATA FROM SPACE
(INTER-AGENCY TASK FORCE, 1979)**

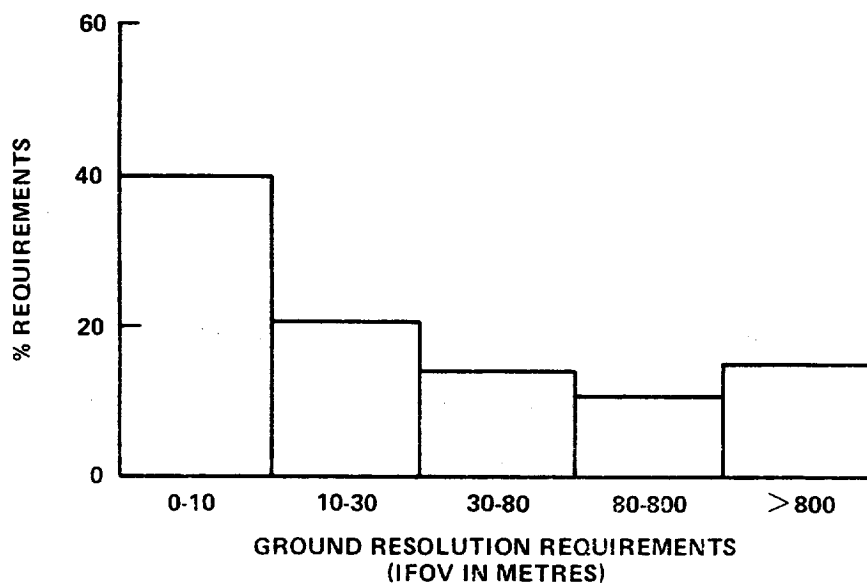


Figure 1. Survey of spatial resolution requirements of major US government agencies. (Inter-Agency Task Force, 1979)

In practice the capabilities of such future systems, and even current ones, are poorly comprehended by many earth scientists including geographers. In large part this arises because users do not properly understand the significance of resolution figures which are quoted. The most commonly available measure is the instantaneous field of view (IFOV), which for many applications significantly over-estimates the capabilities of sensing systems. By borrowing from such disciplines as electrical engineering, optics, and photographic science other measures of spatial resolving power of remote sensing systems have been derived which are often more informative; these are reviewed in the next section. We can obtain a more practical insight into the benefits of improved spatial resolution by examining the results of several empirical simulation experiments of future satellite systems in Section 3. Finally it is important to recognize factors other than spatial resolution which strongly affect the detail of information extractable from remote sensing imagery (Section 4).

Our attention is restricted to the visible and near infrared parts of the spectrum, since this is the source of nearly all higher resolution imagery that has been obtained so far, and extensive collection of data outside of these wave bands at high resolutions is unlikely to take place until the late 1980's or early 1990's.

2. Concepts of Spatial Resolution

Spatial resolution refers to the fineness of detail depicted in an image that is it describes the minimum size of objects on the ground that can be separately distinguished or measured. Transforming this apparently straightforward concept into an operational quantitative measure has proven far from simple. There is no single satisfactory measure of spatial resolution available, nor can values obtained from one method necessarily be readily converted to those derived by another. Spatial resolution turns out to be a much more complex topic than our initial intuitive definition suggests.

Recently it has been suggested (Forshaw et al., 1980) that definitions of spatial resolution can conveniently be assigned to one of four categories: geometrical properties of the imaging system, the ability to distinguish between point targets, the ability to measure the periodicity of repetitive targets and the ability to measure the spectral properties of small finite targets. Examples of these will be reviewed in turn and their relative merits discussed.

2.1 Measures based on the geometric properties of imaging systems

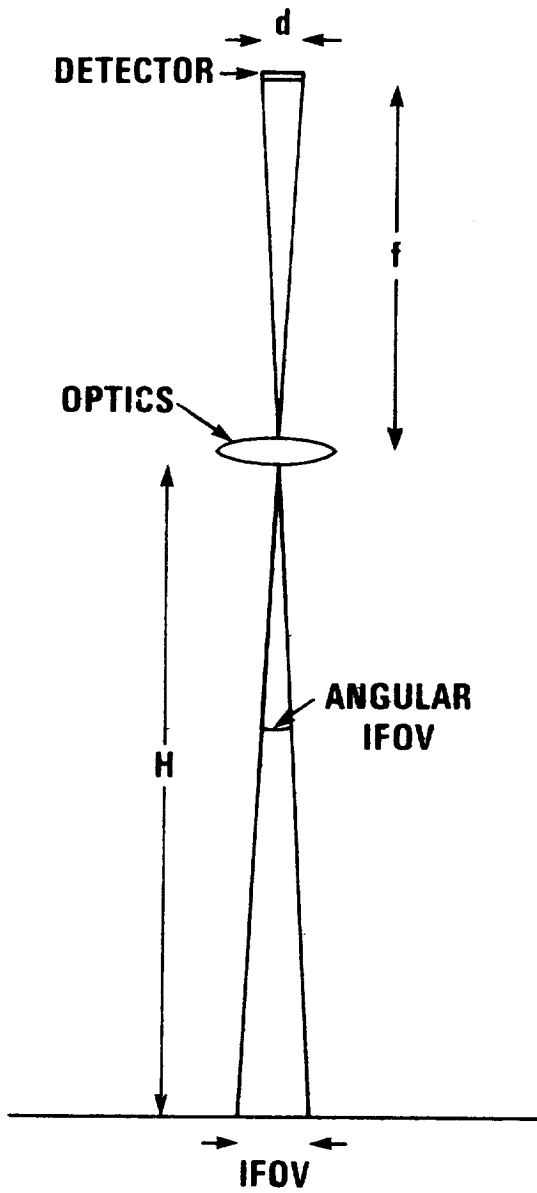
The only measure that needs to be considered in this category is the instantaneous field of view (IFOV). This is probably the simplest measure of spatial resolution available and is in one respect the most important, since it is the most widely quoted for satellite systems. It is usually calculated as follows (see Fig. 2):

$$\text{IFOV} = \frac{H d}{f}$$

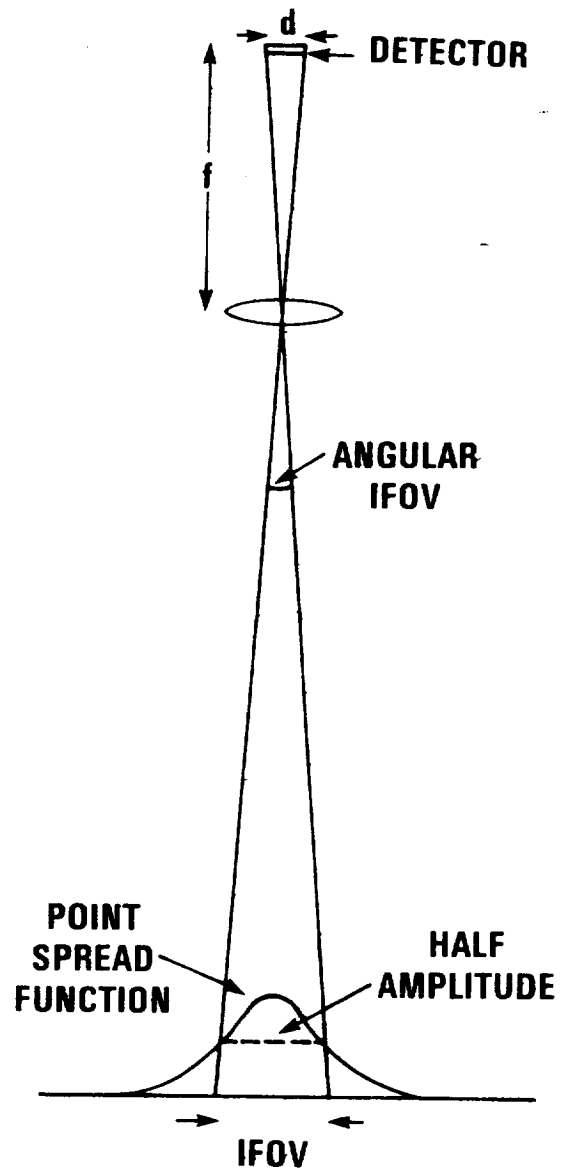
where H is the satellite orbit height

d is the detector size

f is the focal length of the optical system



**GEOMETRIC
INSTANTANEOUS
FIELD OF VIEW.
(IN PRACTICE $f \ll H$)**



**"POINT SPREAD"
INSTANTANEOUS
FIELD OF VIEW**

Figure 2. Definitions of instantaneous field of view (IFOV).

Since detector size has to be defined, this measure is most applicable to sensors with discrete detectors such as line-scanners (Lansing and Cline, 1975) or push-broom radiometers (Thompson, 1979; Wight, 1979) (Figure 3). In the former, images are built up across the track of the satellite by the movement of a mirror and along track by the forward movement of the satellite. Thus the final image is comprised of a matrix of picture elements or pixels. This approach was used in the multispectral scanner system (MSS) of Landsats 1, 2, and 3 and will be used in the Thematic Mapper of Landsat D (see footnote 6 in Table 1). In push-broom radiometers, the need for a moving mirror for the across track elements is dispensed with. On a single monolithic chip of silicon, hundreds to over a thousand detectors can be manufactured along with amplifiers and electronic multiplexing circuits (Thompson 1979): these detectors are electronically sampled such that the entire linear array is read out in the time to advance along track by one resolution element. The push-broom configuration is being adopted in the French SPOT mission and probably will be adopted in the U.S. operational earth resources satellite.

For the MSS of the Landsat series, the IFOV is normally quoted as 79m, (except for the thermal channel of Landsat 3 which is 237m). Colvocoresses (1979b) and Slater (1979) point out that the detector size is reduced due to cladding (walls and adhesives) around the fibre optics through which the photons pass to reach the detectors. This results in an IFOV of 73.4m according to the former and 76.2m according to the latter. Moreover since the altitude of Landsats have varied from 880 to 940 kms, the IFOV has varied from 76m to 81m (Gordon 1980) ignoring the effects of cladding.

The IFOV does not necessarily give the minimum size of objects that are detectable. An object smaller than this size may be sufficiently brighter or darker than its surroundings to change the overall radiance of the pixel, so that it is detectable. Thus roads and rivers narrower than 79m are frequently detectable on Landsat MSS images. The alignment of a linear object is also crucial. Its chances of detection will depend strongly on whether its central axis falls along the centre of a scan line or falls along the boundary between two scan lines (Gurney 1980). In the latter case,

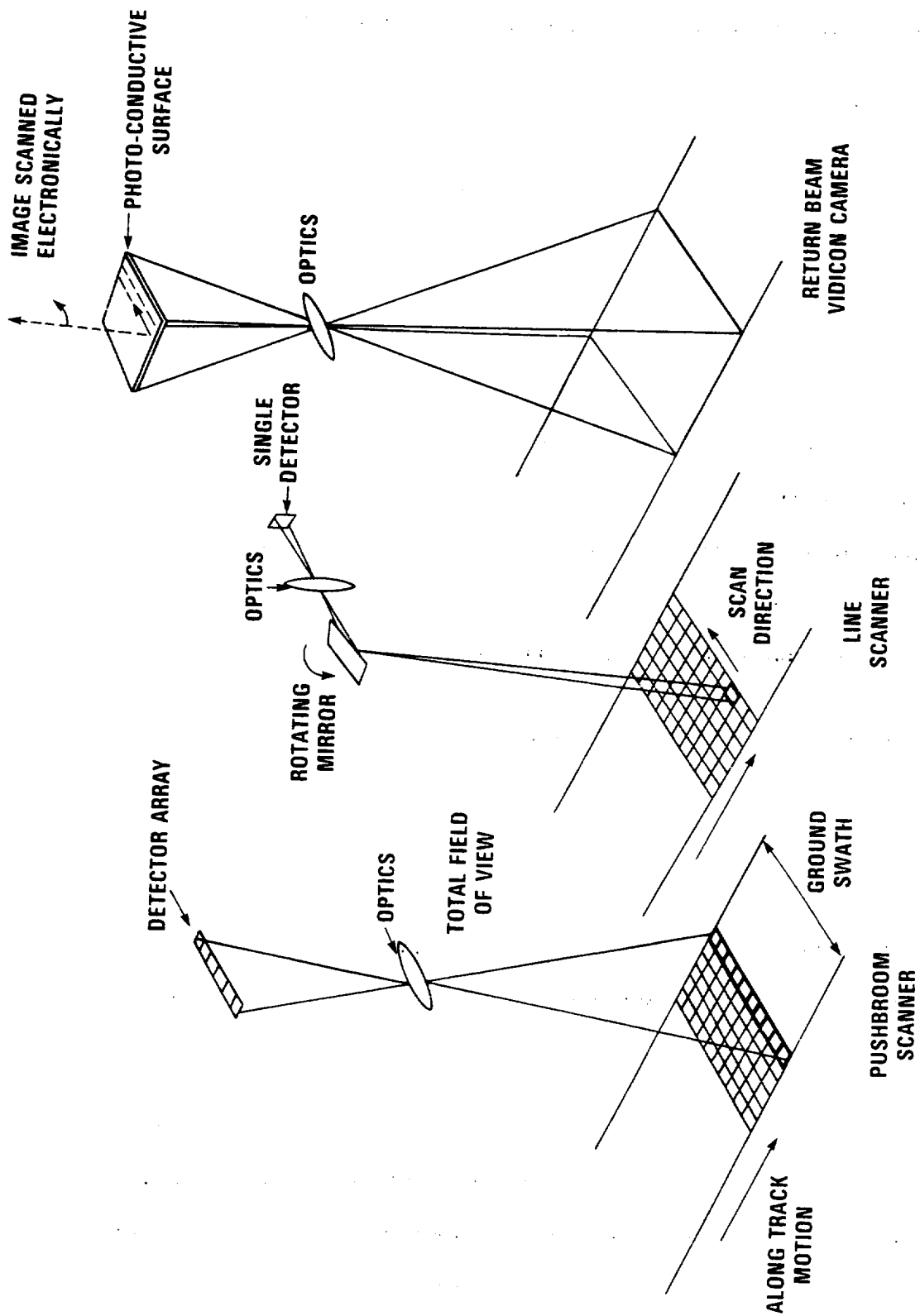


Figure 3. Types of sensing systems used in Earth resources satellites.

Table 1. Principal civilian satellites (past, present and future) for regular collection and dissemination of terrestrial Earth resources data

Satellite System	Spectral Bands	Sensing System ⁵	Date	Spatial Resolution (IFOV in Meters)
Landsats 1, 2	0.5-0.6 μm ; 0.6-0.7 μm ; 0.7-0.8 μm ; 0.8-1.1 μm	Multispectral Scanner ¹	July 72-Jan 78 Jan 75-Present ⁸	79 ⁴
Landsat 3	0.5-0.6 μm ; 0.6-0.7 μm ; 0.7-0.8 μm ; 0.8-1.1 μm ; 10.4-12.5 μm (thermal) ² 0.505-0.750 μm	Multispectral Scanner Return beam vidicon camera	March 78-Present ³ March 78-Present	70 240 (thermal) 40 ⁷
Landsat D ⁶	0.45-0.52 μm ; 0.5-0.60 μm ; 0.63-0.60 μm ; 0.76-0.90 μm ; 1.55-1.75 μm ; 2.08-2.35 μm ; 10.40-12.50 μm . (Also multispectral scanner of Landsats 1 to 3)	Multispectral scanner called the Thematic Mapper	1982 onwards	30 ⁴ 120 (thermal)
SPOT	0.500-0.590 μm ; 0.610-0.690 μm ; 0.800-0.910 μm (multispectral mode); 0.500-0.900 μm (monospectral mode).	Linear array	1984 onwards	20 (multispectral) 10 (monospectral)

¹ The three channel return beam vidicon camera also on the satellites provided little imagery.

² The thermal channel provided little imagery.

³ MSS imagery has had line-start problems, which have now been partially rectified (NASA, 1980a).

⁴ Normally quoted values for Landsats 1 to 3 and Landsat D. In fact, not strictly comparable (see Section 2.1).

⁵ See Figure 2.

⁶ Various problems with the Thematic Mapper may mean that Landsat D is launched with only the multispectral scanner of Landsats 1 to 3 (NASA 1980b, p. 8), and Landsat D' is launched subsequently with the Thematic Mapper.

⁷ Nominal value only since instrument does not have discrete detectors (see Section 2.1).

⁸ Sensing by Landsat 2 was interrupted for a period in 1979 and 1980, but has subsequently been used in 1980.

the likelihood of its being detected will clearly be lower. Whereas objects less than 79m across may be detected; many objects equal to or greater than this value will not be detected. Commonly in Landsat MSS imagery it has been found that medium to low contrast objects are detectable only if they are 250m across or more. One immediately obvious explanation for this is that our ability to detect an object depends on its contrast with its surroundings in relation to the sensor's ability to detect small differences in radiance. This is measured by the signal-to-noise ratio (S/N), which is simply the ratio of the signal to the total noise present. Two types of noise are present in all detectors, namely the photon (or shot) noise due to random fluctuations of photons striking the detector and the Johnson (or Nyquist) noise as a result of thermal effects in the sensor. Various other types of noise exist specific to the particular sensor (Baker and Scott, 1975). Figure 4 illustrates the character of the S/N ratio. Signals comparable to or smaller than the combined noise level will be undetectable. Moreover the signal from sensors will usually be quantized for transmission to the ground surface (though not for the RBV sensor of Landsat 3), and for subsequent digital analysis. This digitization will further add noise to the signal. The impact of different quantization levels on the use of remotely sensed data has recently been examined by Tucker (1979). Apart from hardware noise we can consider atmospheric effects as a noise-like phenomenon which can increase or decrease the signal received by the sensor (Fraser, 1974; Slater, 1975a). The net effect is to reduce the contrast of an image. Thus, the minimum size of objects which can be detected in a given scene will be a function of local atmospheric conditions. Wiersma and Landgrebe (1978) also refer to scene noise, caused by those components of a scene reducing the accuracy with which pixels are assigned to the correct land cover class. For example soil variation may confuse multi-spectral classification of crop types. The significance of this point is dealt with further in Section 3.

Various blurring effects will also be present and lead to further image degradation (Forshaw et al., 1980) and thus will contribute to the disparity between the estimate of resolution based on the IFOV and the realizable resolution in terms of the minimum size of objects that can be distinguished. These are due to optic phenomena such as aberration and diffraction. The former is

much more important than the latter at the wavelengths in the visible and near infrared but at longer wavelengths in the microwave, the reverse is the case. Blurring will also be caused by motion during imaging due both to the forward movement of the satellite and to the across-track movement of the mirror in scanning systems. If a multispectral image is produced, the extent to which the images are not geometrically registered will also produce a blurring effect.

It is usual to equate pixel size in imagery with the IFOV, but this need not be the case. For Landsats 1 and 2 MSS data the IFOV and the pixel size are indeed essentially the same. In the along track direction, the pixel size equals the ground track velocity divided by the mirror scan frequency but across track the continuous signal could in theory be sampled at any arbitrary rate. In fact it is chosen to give a pixel width the same as the along track pixel size but with an overlap between adjacent pixels of 23m. Hence pixel size for the Landsat MSS is sometimes quoted as $79\text{m} \times 56\text{m}$ (General Electric, undated). The data on Landsat 3 digital tapes have been resampled using a cubic convolution algorithm to produce pixels with dimensions of $57 \times 57\text{m}$ (Holkenbrink, 1978) in which case pixel size and IFOV are dissimilar. However this resampling which produces smaller pixels will not improve the actual spatial resolution and may decrease it slightly.

The previous discussion demonstrates the limitations of the IFOV as a measure of spatial resolution. In the following sections, we discuss various measures which attempt to take these factors into account in estimating spatial resolution. However, first, we note that an alternative definition of IFOV has been proposed, based on the point spread function (PSF) of an imaging system. The point spread function describes the distribution of energy in the image plane, when a point source is imaged. In other words it describes the resultant image of a point source. This image is never a simple point due to such factors as the motions of the spacecraft and imaging mirror lens' properties as well as atmospheric influences. The point spread function IFOV is defined as the width of the point spread function at its half amplitude values (figure 2). The IFOV of 30 metres normally quoted for the Thematic Mapper of Landsat-D is based on this measure; the corresponding point

spread IFOV, for the Landsat MSS is somewhat greater than that of the geometric IFOV namely 90m rather than 79m (Landgrebe et al., 1977). The point spread instantaneous field of view is in fact closely related to measures dealt with in the following section.

2.2 Measures based on the ability to distinguish between point targets

The most commonly used definition in this category of resolution measures is the Rayleigh criterion (Perrin, 1966; Slater, 1975a). Even if a lens is completely aberration-free, the resultant image of a point-source, will not itself be a point, but will consist of a central bright disk surrounded by faint dark and light rings. This pattern is known as the Airy pattern, and arises because of diffraction effects: this pattern describes one particular type of point spread function (see section 2.1). The Rayleigh criterion for distinguishing between two targets is based on two equal intensity point sources imaged by an unobstructed aberration-free, circular aperture. It states that the two targets will be just resolved if the central peak of the image of one source lies on the first dark ring of the second. The angular separation (θ) is simply calculated as (Slater, 1975a):

$$\theta = \frac{1.22 \lambda f}{1000}$$

where λ is the wavelength in micrometers.

f is the usual f-number of the lens.

From θ and the height of the sensor above the ground, a measure of resolution in terms of ground measures can be derived.

Most remote sensing targets are of course not point sources, and with this in mind Otterman (1969) derived a resolution measure for extended circular sources which is more relevant to remote sensing. Estimates for square or rectangular objects would probably not be very different. He showed that the diffraction limited resolution for such sources is almost six times coarser than that for point sources.

In practice of course, lenses are not aberration-free and as discussed in the previous section there are many other properties which will degrade the image and hence increase the minimum separation that is detectable. Measures of this category consequently gives an indication of the absolute resolution that is achievable by a lens.

2.3 Measures based on the ability to measure the periodicity of repetitive targets

Measures based this property arose principally from work on photographic images (Scott and Brock, 1973; Shaw, 1979) though they have been applied to images derived from other sensors (e.g. Lavin and Quick, 1974; Buchtemann, 1974). They are based on the observation that if one images sets of parallel linear objects, the contrast between them and their background will appear to be lower as their spacing decreases, until a step is reached when the contrast is so small that the linear objects are indistinguishable. Values of resolution derived in this way are consequently expressed by spatial frequency measures such as line pairs/mm confusingly often abbreviated to lines/mm. Since the linear targets used often have a sinusoidally-varying tone, values are also expressed in cycles/mm. Somewhat against standard practice NASA (1973b) has expressed such values in terms of single lines/mm or in terms of half-cycles/mm, an approach which has not found favour by all (Slater, 1975b).

Modulation (M) is the measure of contrast most frequently used in this context.

$$M = \frac{E_{\max} - E_{\min}}{E_{\max} + E_{\min}}$$

E is variously defined as object radiance (Welch, 1977; Smith, 1978), luminance or photographic exposure values determined from microdensitometer readings (Perrin, 1966; Welch, 1971), transmittance or intensity (Scott and Brock, 1973). M consequently has a maximum value of 1.0. The ratio of the image modulation M_I to the object modulation M_O is known as the modulation transfer factor. If we plot the transfer factor against spatial frequency the resultant curve obtained is called the modulation transfer function (MTF) (Steiner and Salerno, 1975) (Figure 5). Usually the MTF curve is derived only for high contrast sinusoidal targets but can also be derived for square-wave targets.

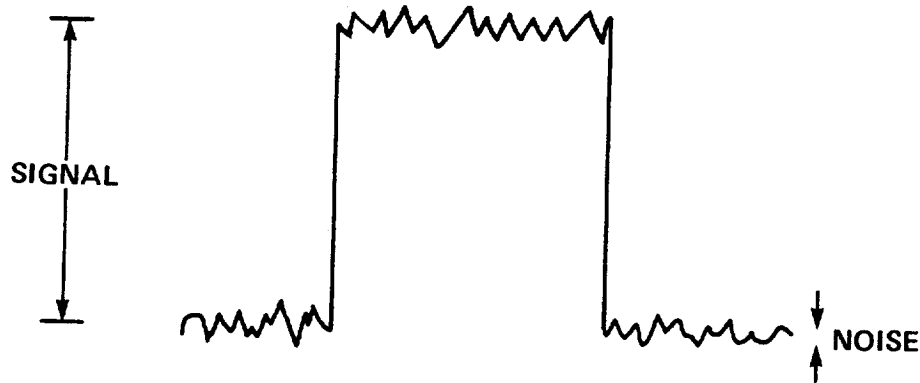


Figure 4. Signal to noise ratio (S/N).

Various measures of resolution can be derived from MTF curves. For example, we can calculate the spatial frequency at which the modulation falls to a set proportion of its maximum value. The effective instantaneous field of view (EIFOV) is half the value of the spatial frequency for which the modulation of an object with a sinusoidal distribution of radiance has dropped to 50% of its original value as a result of the modulation transfer function of the imaging system (Slater 1975b; NASA 1973b) (fig. 5). The ground measurement G in metres is derived from the estimate of line pairs per millimetre (L) displayed on the actual images by this equation:

$$G = \frac{1}{1000SL}$$

where S is the scale of the imagery. The EIFOV of the Landsat MSS (using the 0.5 MTF value) is 66m, which is rather smaller than the IFOV of 79m (Welch 1977). If the full cycle definition is used, the value is 132m. Using the MTF curve for the return beam vidicon camera given in General Electric (undated), an estimated EIFOV of 38.8m is obtained. The IFOV of the Thematic Mapper of 30m corresponds to a modulation transfer factor of 0.35 for a square wave response (Blanchard and Weinstein, 1980). From data quoted in Morgenstern et. al. (1976) it appears that the EIFOV is approximately 45 meters. An alternative approach is to derive a demand modulation curve (also called the threshold modulation or aerial image modulation curve) which is a plot of the minimum image modulation required to produce a response in a sensor as a function of spatial frequency. Thus when plotted on a graph of the modulation transfer factor against spatial frequency (Figure

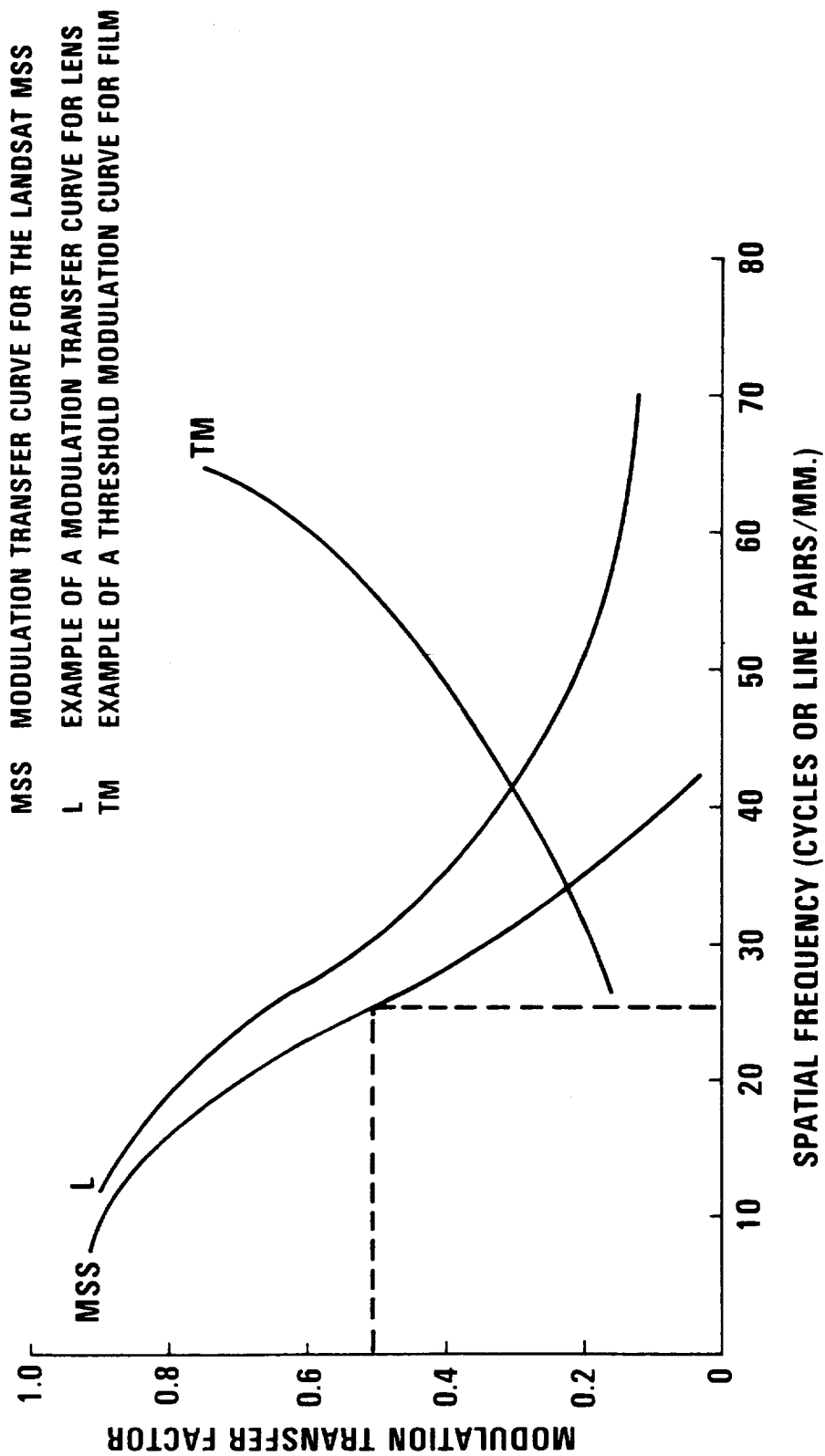


Figure 5. Modulation transfer functions of the Landsat MSS and a typical lens (L), with a threshold modulation (TM) curve for film. Intersection of the last two curves indicates the finest resolution possible with this combination of lens and film. Derivation of the effective instantaneous field of view (EIFOV) is shown for the Landsat MSS.

5), the curve plots upwards from left to right. The intersection of this curve with the system MTF gives the limiting resolution of the system. This approach has been applied most commonly to photographic film (Welch 1972; Smith, 1978) when the curves are usually called threshold modulation (TM) curves. Since MTF curves are almost invariably non-linear, use of a single value can be misleading. A more comprehensive estimate is to calculate the equivalent bandwidth, which is obtained by replacing the MTF curve by a rectangle of equivalent area and giving the upper bound as the value of limiting resolution, though even this will be a simplification (Smith, 1978). A further refinement with reference to visual interpretation is to calculate the modulation transfer function area (MTFA)

$$\text{MTFA} = \int [M(k) - D(k)] dk$$

where $M(k)$ is the imagery system MTF and $D(k)$ is the detection threshold curve for the human visual system (Schindler, 1979). Despite the apparently self-evident relevance of such measures for assessing the usefulness of space imagery for photo-interpreters this approach does not appear to have been considered.

MTF curves can be derived by imaging bar targets of varying width in the laboratory, but are preferably derived from large bar targets on the ground. Since standard resolution targets of sufficient size are unavailable for space imagery, MTF curves have been derived from edge (Corbett, 1974) or line targets (e.g. Welch, 1974) such as coast lines or roads, and by using intermediate images from aircraft flying under the orbiting sensor (e.g. Schowengerdt, 1976).

Where a sensor does not possess discrete detectors the IFOV cannot be directly calculated and estimates of resolution based on MTF are especially appropriate. This is the case both for photographic products from sensors such as the Earth Terrain Camera of Skylab and for the return beam vidicon (RBV) camera on board Landsats. The latter are similar to television cameras: when the camera is shuttered the images are stored on a photo-conducting surface which is then scanned initially by an electron beam and an analogue signal derived from the depleted reflection within the image tube (Eastman, 1970; Baker and Scott, 1975). In Landsat 3, the RBV cameras were

configured to give monochromatic imagery with a narrower total field of view and hence with much better resolution than that of the RBV cameras and MSS on board Landsats 1 and 2. The EIFOV of the latter derived from laboratory derived curves (General Electric, undated) is about 39m. The pixel size of Landsat 3 RBV images is rather smaller than this, namely 21.8m X 23.8m (RCA, 1977). As already indicated in Section 2.1, such pixel sizes may well give an over-estimate of the actual resolution.

Although the MTF approach provides a much more comprehensive description of system resolving power than measures based on geometric properties or the ability to distinguish between point targets it has its limitations. It is based on high contrast objects which are long compared with their width, and most ground targets do not have this form. Hence measures derived from MTF curves may imply an overly-optimistic performance to the unwary.

2.4 Ability to measure the spectral properties of small finite targets

The automated classification of images is of increasing importance (Swain and Davis, 1978; Townshend, 1981). Such classification is usually highly dependent on the fidelity of the spectral measurements that are recorded by the sensor. Consequently resolution measures which indicate the minimum size of targets for which the spectral properties can be recorded to a given of accuracy are potentially of great value. Colvocoresses (1979b) suggested a measure of resolution called the effective resolution element (ERE) based on the size of area for which a single radiance response (value) can be assigned with reasonable assurance that the response is within 5% of the value representing the actual relative radiance. He derived values of 86m for the Landsat MSS, 30m for the Landsat 3 RBV cameras, and gives an estimated value of 35m for the Thematic Mapper of Landsat-D. Subsequently Strome (1979) suggested a refinement of this idea and defined a modified ERE based on a single homogeneous area surrounded by a much larger homogeneous one, whose measured radiation is 30% of the full-scale of the measuring instrument. The ERE is defined as the

minimum area for which spectral properties of the centre can be assigned with at least 95% confidence that the values differ from the actual parameter values by no more than 5% of the full scale of the measuring instrument (Strome, 1979).

Estimation of this area demands we know the probability distribution of the observed signal which is estimated from the point spread function and system noise. Derivation of such distributions for various sensors are provided in Forshaw et. al. (1980) but as yet no direct quantitative estimates of this potentially very useful measure of spatial resolution using this method have been made. We can gain an indication of the size of such estimates by reference to earlier work of Norwood (1974), who modelled the performance of Landsat multispectral scanners using MTF, system noise and accuracy of radiometric calibration. Graphical results (Norwood, 1974, Table 5) indicate that for typical agricultural scenes there will be a 5% error in radiance values for the Landsat MSS, channels 4 & 6, when field size is approximately 125m and 200m respectively. Norwood (1974) points out that the error for small field dimensions will tend to be dominated by the MTF error, and for larger fields diminishes to asymptote dependent on noise and calibration error.

If our major concern is classification of images then it would be useful to know what is the minimum area occupied by a particular cover type that can be classified to a certain degree of accuracy with a given probability. This is discussed further in Section 3.

2.5 Implications for users

It is clear that no single definition of spatial resolution is possible, since different users are concerned with different image properties and these demand alternative measures of resolution. Very different estimates of the resolution may therefore be obtained for the same sensor as can be seen in Table 2 which summarizes the various estimates of the resolution of the Landsat MSS. Thus those particularly concerned with spectral properties as is often the case for those mapping land cover by computer-assisted methods should find measures like the ERE most appropriate. On the other hand if analysis is based primarily on traditional visual photo-interpretation methods

Table 2. Estimates of the resolving power of the Landsat MSS.

Resolution Measure	Source	Resolution (meters)
1. IFOV – geometric	NASA 1972	79
2. IFOV – geometric	Slater, 1979	76.2
3. IFOV – geometric	Colvocoresses, 1979	73.4
4. IFOV – geometric (min. altitude)	Gordon 1980	76
5. IFOV – geometric (max altitude)	Gordon 1980	81
6. Pixel size	General Electric (undated)	79 X 56
7. Pixel size – resampled (Landsat 3 CCT's)	Holkenbrink, 1978	57 X 57
8. IFOV – point spread	Landgrebe, et al., 1977	90
9. EIFOV – half cycle	Welch, 1977	66
10. EIFOV – full cycle	Welch, 1977	135
11. ERE	Colvocoresses, 1979b	87
12. Modified ERE – estimate for Channel 4	Norwood, 1974	125
13. Minimum classifiable area	Shay et al., 1975 General Electric, 1975	500 X 350 320 X 220

as is often the case for those making inferences about sub-surface conditions such as hydrological or geological ones, then measures based on the MTF should be preferable. In practice a user of remotely sensed data may only have an IFOV value available as a measure of spatial resolution. As a comparative measure this can be useful, so long as its limitations are clearly understood. Thus the smaller IFOV of the Thematic Mapper compared with the MSS should lead to an approximately ninefold reduction in the area of detectable targets with the same spectral properties, spatial characteristics and contrast with their surroundings. It should be apparent however that the IFOVs cannot simply be translated into the ground measurements of the smallest detectable objects. The latter will depend on many factors, not least of which are the terrain properties themselves which are being observed. These will affect the spectral response of objects and their surroundings and hence largely contribute to the contrast of objects with their surroundings and thus to the ability of a sensor to resolve them.

3. Benefits of improvements in the resolving power of future satellite systems

It is important that the effects of improving the spatial resolution of satellite images are understood. Firstly, the users of such data should be aware of the capabilities of systems due to be launched in the near future. Secondly the designers of future systems require this information so that sensors with appropriate spatial resolution are eventually launched. The consequences of finer resolution on the accuracy of automated classification and on visual interpretation are discussed.

3.1 Automated classification

The potential benefits of better spatial resolution have been assessed in several empirical simulations using data obtained from sensors in aircraft. The resultant imagery is progressively degraded to assess the effects of decreasing resolution on the usefulness of the images. Most of the experiments have carried out such degradation simply by taking regular square blocks of the original aircraft pixels and averaging them to create new pixels (e.g. Clark and Bryant, 1977; Kan et al., 1975; Thompson et al., 1974). Such simple averaging does not fully take into account possible differences between the simulated imagery and the actual imagery from satellite-borne sensors in

terms of properties such as their point spread functions and signal-to-noise ratios. More sophisticated algorithms have therefore been applied by some workers to the original aircraft imagery to simulate satellite imagery more closely (e.g. Sadowski and Sarno, 1976; Morgenstern et.al., 1976). The principal objective of nearly all these experiments has been to assess the effects of changing spatial resolution on the classification accuracy of land cover types identified by computer-assisted automated methods. The latter basically rely on the application of multivariate statistical procedures, the variables usually being the values of the separate spectral bands. Identification of classes is either *a priori* or *a posteriori*, the two approaches being termed supervised and unsupervised in remote sensing parlance (Swain and Davis, 1978). The usefulness of the images is then usually assessed according to the proportion of an area which is correctly classified.

a. The effects of scene noise

Results from these experiments have often been the converse of what we might expect since overall classification accuracy has been found to improve as resolution is coarsened (Figure 6) over the range of resolutions considered. Explanation for this paradoxical conclusion has usually been couched in terms of the internal heterogeneities within individual cover types. For example an area of woodland when viewed at high resolution will normally be found to be far from spectrally homogeneous due to the presence of what Wiersma and Landgrebe (1978) term scene noise. Some areas of crowns will be in shadow, others will be strongly illuminated; openings in the crown cover may reveal the herbaceous cover below; the amount of reflective leaf matter and woody tissue will vary between trees. As a second example, consider a suburban residential area where high resolution imagery will reveal many separate individual cover sub-types, including roofs, road surfaces, grass cover, trees and many others.

Automated classification of either of the previously described cover types may well lead to errors if their separate component heterogeneities are resolved. Some errors may be termed artificial classification errors. For example, although an area is considered in reality to be completely "suburban residential", classification of small areas of trees as woodland may be regarded as errors

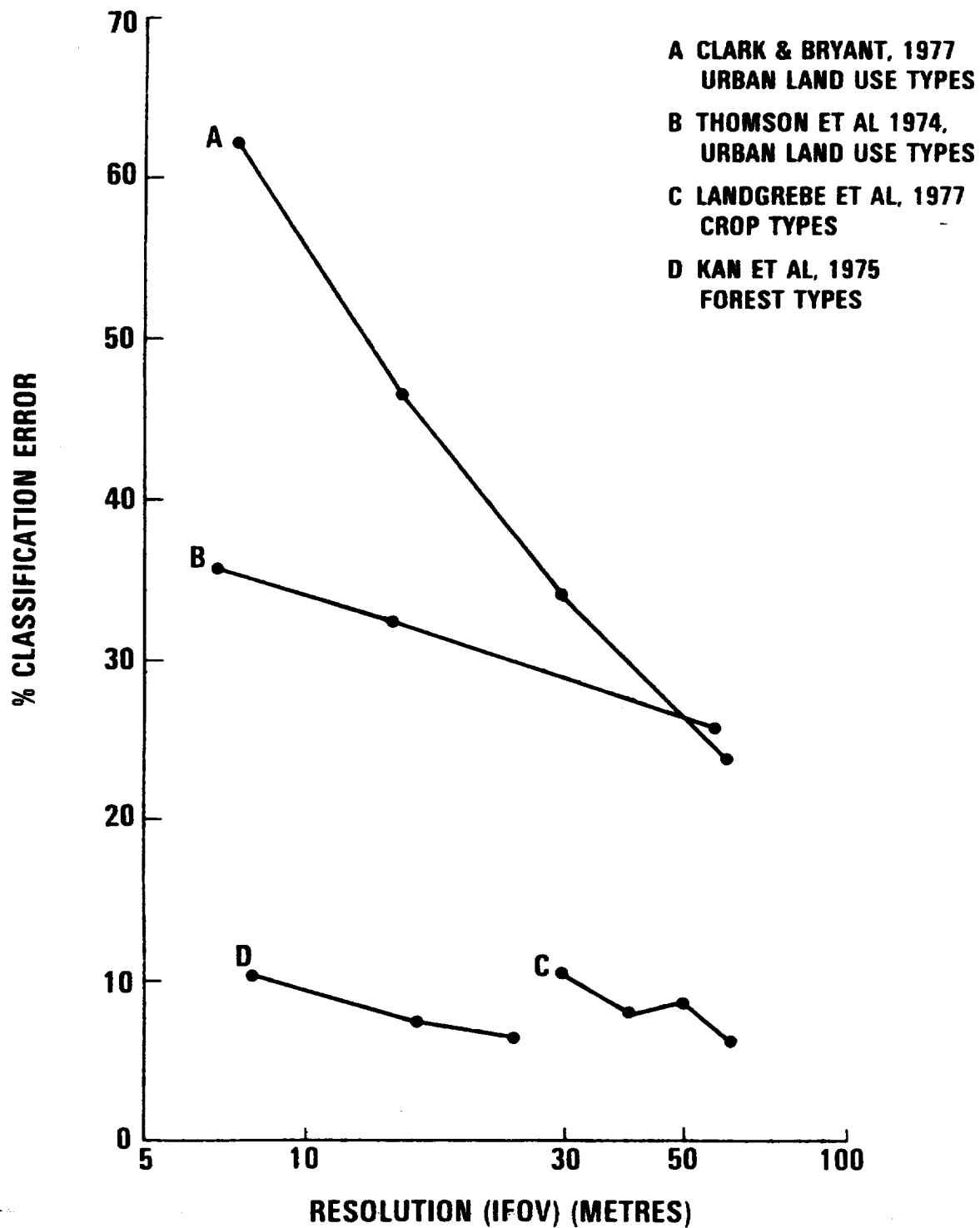


Figure 6. Decline in classification errors with coarser resolution principally as result of scene noise. Note that errors were calculated in different ways in the studies, so that absolute numerical values are not comparable between studies.

by users of the resultant maps, even though trees exist on the ground. Similarly within an area of wildland forest separate identification of small openings in the canopy may be regarded as irrelevant or confusing detail by some users, but as correct by others depending on their scale of interests. However some errors may be genuine. Areas of dark shadow can be misclassified as water: crown configuration will affect the spectral response of trees and may lead to trees being assigned to incorrect classes. Coarser resolutions will tend to reduce scene noise by averaging out these internal heterogeneities and giving a spectral response with much lower variance and thus classification accuracy is likely to be increased (Sadowski et. al., 1977).

Mobasserri et al. (1980) have recently modelled the performance of a multispectral scanner in relation to variations in scene correlation. They showed, using hypothetical though realistic data, that the higher the spatial correlation within the scene the slower will be the improvement in classification with increasing IFOV.

b. The effects of boundaries

The results quoted above give only a partial indication of the effects of changing resolution, since they do not explicitly consider the effects of boundaries between the cover types being classified as contradistinction to those within cover types discussed above. Pixels falling across such boundaries will record a mixed response from the two cover types. Moreover even pixels not directly over the boundary will be affected by the adjacent land cover types as indicated by values in the instrument point spread function. Radiation scattering by the atmosphere will cause additional contributions from surrounding terrain. Classification may assign a mixed pixel to one of its constituent classes especially if a class occupies a large proportion of the pixel. If the proportions are more equitably distributed then the class to which it is assigned becomes more uncertain and this class may even be one which is not found within the pixel at all. To a certain extent the problem of mixed pixels can be overcome by designing algorithms to estimate proportions directly (e.g. Nalepka and Hyde, 1972; Horowitz et al., 1975). Despite such efforts boundary pixels are inherently more difficult to classify and as they increase proportionately, so classification

accuracies will have a tendency to decline. Thus the spatial frequency and configuration of boundaries and consequently the area and shape of land cover units will affect classification accuracy.

We can examine this effect by reference to three resolution degradation experiments in which the classification accuracies were assessed when boundary pixels were excluded (figure 7a) and for the same scenes when the boundary pixels were included (figure 7b). For the woodland types in the study of Sadowski and Sarno (1976) it can be seen that as resolution coarsens, classification accuracies tend to increase. For the other two studies no marked trend is apparent except for the coarsest resolution in test run 1 of the investigation of Morgenstern et al. (1976).

When the whole scene including boundaries is analyzed, the cover types examined by Morgenstern et al. (1976) now show a consistent decline especially marked for the second traverse. Classification accuracies in the study of Thompson et al. (1974) show a marked decline at higher IFOVs. Results from the latter experiments are especially informative since they are stratified into field size classes. Only the largest field size class shows an increase in accuracy at the highest IFOV. The curve for the results of forest classification still shows an upward trend but it is less steep when boundaries are included.

c. Joint affects of scene noise and boundaries

From these results we may infer that changes in classification accuracy with spatial resolution arise from two conflicting trends. Firstly, the variance of spectral response or scene noise will decline with coarsening resolution which will usually help improve classification accuracy. The strength of improvements will be primarily controlled by the degree of spectral heterogeneity within a cover class. Secondly, the proportion of boundary pixels will increase with coarsening resolution and this will tend to lower classification accuracies. The form of the curves in Figures 5 and 6 thus depends on the relative importance of these trends between any two resolutions. These trends themselves are largely a function of the spatial properties of the terrain which is being observed. Different terrain types with contrasted boundary densities and land cover

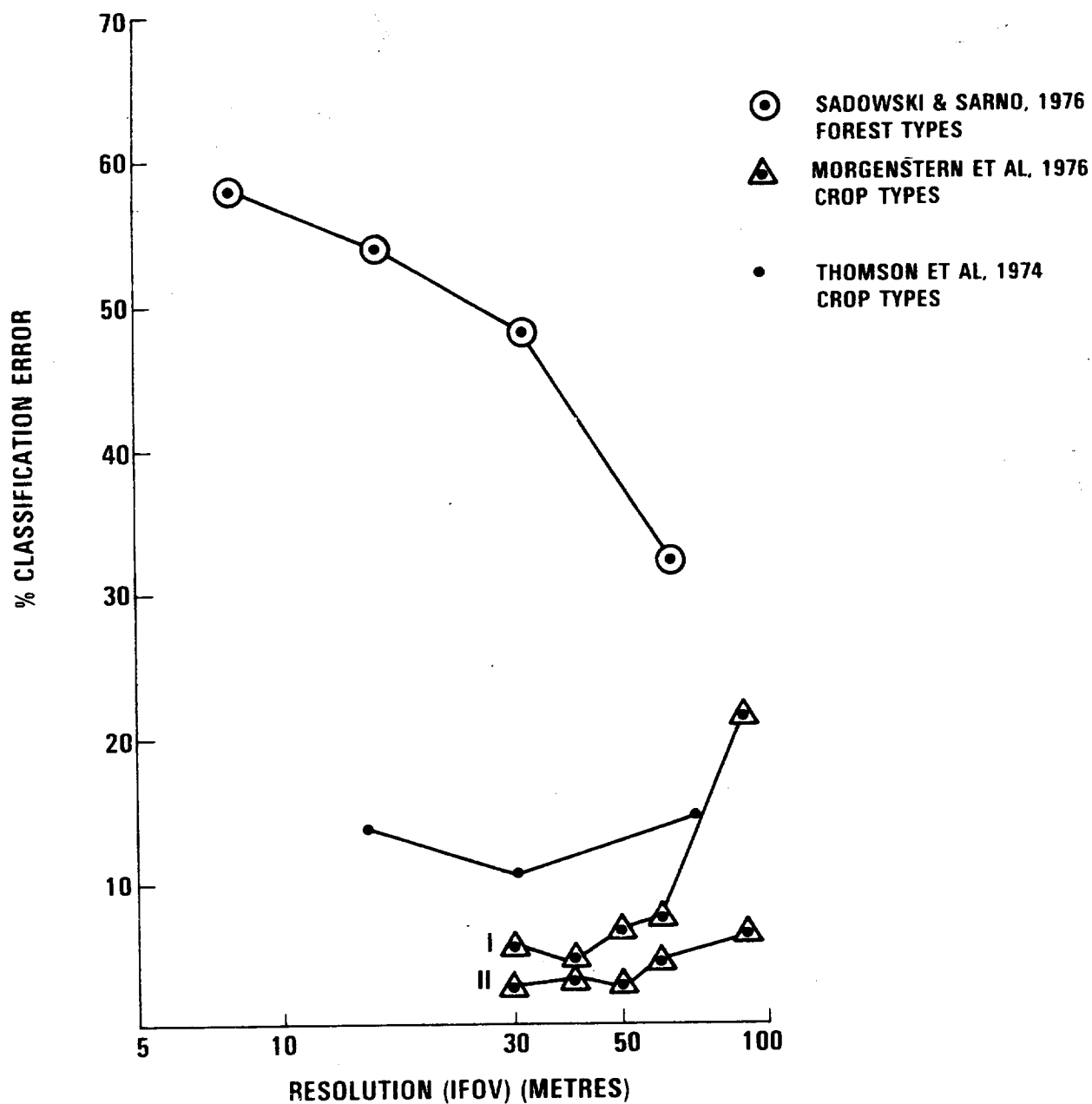


Figure 7a. Changes in classification accuracy with spatial resolution (IFOV):
a. with boundaries excluded.

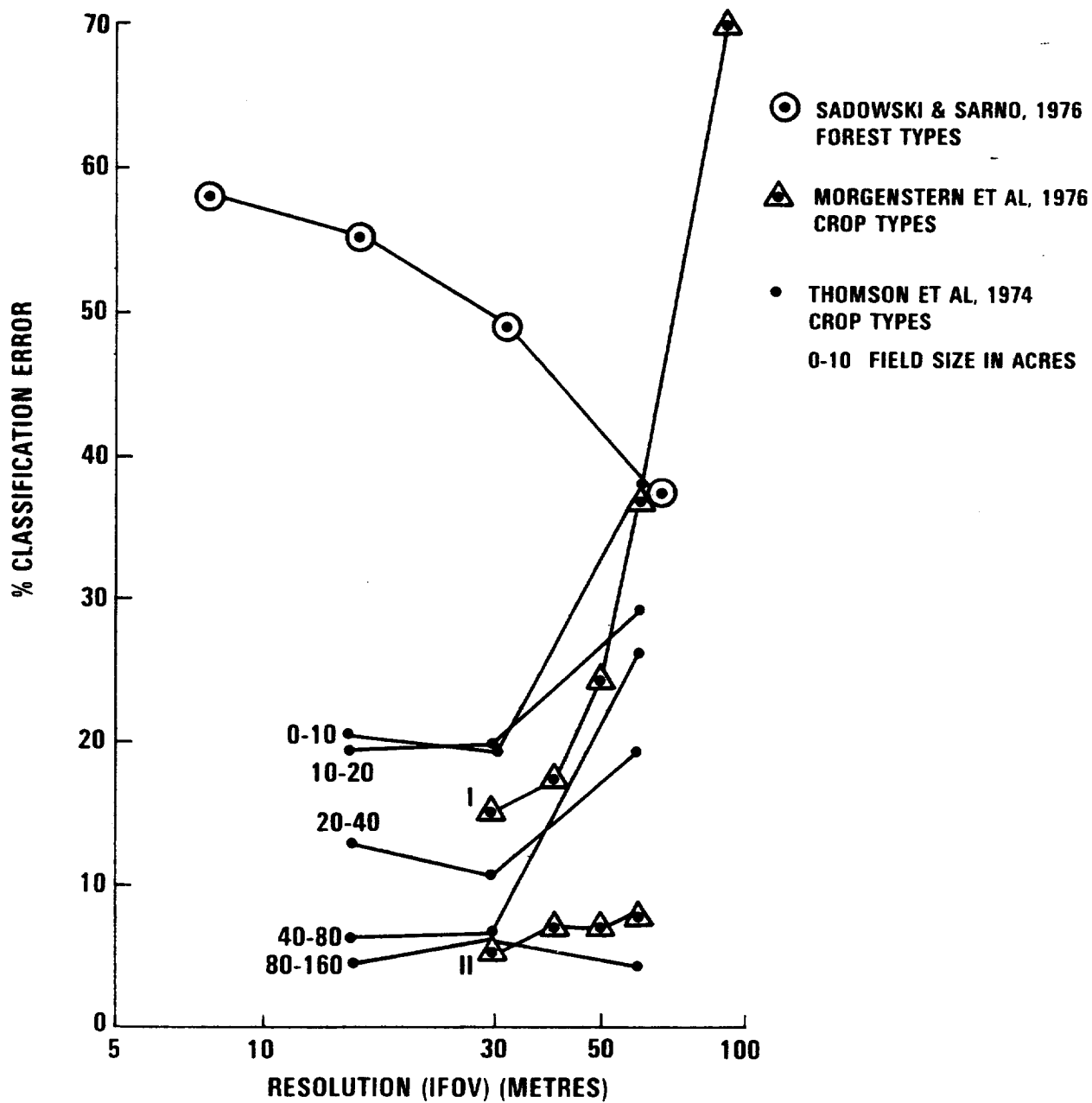


Figure 7b. Changes in classification accuracy with spatial resolution (IFOV):
b. with boundaries included.

heterogeneities will thus demand different spatial resolutions for optimal classification accuracies. Improvements in the spatial resolving power will make automated classification of land cover feasible from satellites in many parts of the Earth, where currently this is impossible because of the small size of their land cover units. But, we must also recognize that higher resolution may not necessarily improve classification accuracy in all terrain types, and it may be advisable actually to degrade higher resolution imagery for some tasks. The latter may be particularly appropriate if classification is based on simple per-point classification (i.e. using only the spectral information for each pixel and no information from surrounding areas) which is the most common type used at present. However the extra information contained within higher resolution images can be exploited by using measures of image texture (e.g. Haralick, 1979) or by using contextual algorithms which classify a pixel using its relationship to other previously classified pixels (e.g. Swain et al., 1980). On the other hand, computation times of such classifiers may be significantly higher than conventional per-point classifiers.

Various estimates have been made of the minimum size of area which can be satisfactorily classified. Work by General Electric (1975) suggests that an area four by four pixels in size is the minimum. However it has been suggested that the number of boundary pixels should be no greater than half the total area to be classified and this implies for square areas that the total number of pixels should be approximately 60 (Shay et. al., 1975) corresponding to a square whose sides are between 7 and 8 pixels long. For Landsats 1 to 3 this means the minimum classifiable area will be approximately 320 by 220 meters or 500 by 350 meters depending on which criterion is used (taking the across scan overlap into account). For the Thematic Mapper of Landsat-D the corresponding figures will be approximately 120m and 230m and for the multispectral sensor of SPOT the values are approximately 80m and 150m.

3.2 Visual interpretation

Relatively little work has been done on the effects of changing resolution on the visual interpretation of images from future satellite systems, though there exists an extensive literature on the

human assessment of image quality in general (see Schindler [1979] and Bylander [1979, Chapter 3] for recent reviews). One example where tests were performed on degraded aircraft images to simulate satellite imagery showed a simple monotonic decline of classification accuracy with resolution for four out of five cover types (Lauer and Thaman, 1971). This result is clearly at variance with many investigations of computer-assisted classification. Visual interpretation is more important however for those tasks where inferences have to be made about sub-surface conditions as in geological or geomorphological or hydrological survey. Recently return beam vidicon (RBV) imagery from Landsat 3 have become available with an estimated IFOV of about 40m (RCA Government Systems Division, 1977). Visual inspection of examples of such imagery suggests that it is often significantly more interpretable than Landsat MSS imagery (Justice and Townshend, 1979), though its advantages are a function of the spatial terrain frequencies that are present (Townshend et al., 1979; Townshend and Justice, 1979). It is clear that improvements beyond the 30m IFOV of the Thematic Mapper of Landsat-D will yield useful data for the visual interpreter. For example Merifield and Lamar (1975) in mapping geological faults found significantly more value in Skylab photography with an IFOV equivalent of 15 to 20m than in photography with IFOV equivalent of 30-40m. On the basis that visual interpretability increases logarithmically with linear increases in image resolution, Welch (1977) estimated that on average there will be an approximate 40% improvement in image interpretability due to the increase in IFOV of the Thematic Mapper compared with the MSS of Landsats 1, 2, and 3.

4. Significance of other factors affecting the information content of remotely sensed data

Many factors other than spatial resolution strongly affect the information content of images. There is clear evidence that the new spectral bands chosen for future Earth resource satellites (Table 1) will be significantly better than those of the Landsat multispectral scanner (Tucker, 1978; Podwysocki et al., 1979). Moreover there are several factors which will have a direct impact on the fineness of detail extractable from remotely sensed data.

None of these is more significant than the spatial variability of terrain itself, since improvements in resolving power will only be significant to the extent that the terrain itself has spatial frequencies of a size which will be better depicted. Although this point is self-evident to many, if not most, users of remote sensing data, quantitative knowledge of the inherent spatial variability of terrain attributes is generally poor. The variability of soil properties forms a notable exception (e.g. Campbell, 1978; Webster, 1978; Webster and Beckett, 1970; Mitchell et al., 1979) though it is not straightforward to convert the results of such studies into a form suitable for estimating the capabilities of present and future satellite systems. Estimates of field size distributions have been made for several different countries, but the most comprehensive ones have relied principally on space images themselves to derive the measurements (e.g. Podwysocki, 1976; General Electric, 1975) and consequently a significant bias will be introduced for smaller fields. Many local studies of the morphometry of landforms have been made, but wide scale generalizations are not easy to make from them. Information on the spatial variability of other terrain attributes in a form suitable for conversion to resolution requirements is usually much poorer. Clearly there is a need for improved quantitative information about the spatial variability of terrain attributes if their significance in affecting the usefulness of remote sensing data is to be fully appreciated.

The amount of information that can be extracted from images is also a function of image processing techniques. If we digitally enhance the edges present in an image for example by convolution of the image data with a Laplacian filter (Steiner and Salerno, 1975) and add this image to the original then we will usually obtain a resultant image which has a much sharper appearance and which visually appears to have better spatial resolution (e.g. Hord, 1977). Application of Fourier methods either optically or digitally in which a high-pass filter is used, would also have the effect of enhancing the fine detail present in the image. Yet a further alternative is to design an optimum restoration filter based on the imaging system point spread function of the specific sensor system used. This has been successfully carried out by McGillem et al. (1975) for Landsat 1 imagery.

The benefits acquired from such products have to be set against the computation times and costs, which can often be substantial. However, even simple contrast stretching can produce a much more interpretable product for the human interpreter with much more visible detail (e.g. Lillesand and Kiefer, 1979, 566-7).

Finally it is relevant to point out that in the future political factors may restrict the availability of higher resolution imagery. There is an understandable concern in some countries that high resolution data of their sovereign territory should not be made widely available because of the insight such imagery may reveal about their resources. Proposals have been made at the United Nations to restrict the availability of high resolution data, subject to the country itself granting permission. Although it may be tempting to specify a given spatial resolution value beyond which imaging is not allowed, this will inevitably be inequitable since difference in inherent terrain variability itself will strongly affect the quality of information that is extractable. The same sensing system may in effect be a high resolution system for one terrain type and a low resolution system for another.

5. Conclusions

Just as the user of maps needs to know their scale so the user of remotely sensed images needs to know their spatial resolution. However depending on how these data are to be used, quite different measures of spatial resolution are appropriate. The geometric instantaneous field of view that is often quoted has comparative values, but has significant limitations. Other measures have been derived, which often give a better indication of the usefulness of the data. Measures based on the modulation transfer function have significant advantages for visual interpretation whereas those based on the spectral properties of small finite objects are preferable for tasks involving automated classification.

Changing the spatial resolution of satellite images affects the utility of satellite images in ways which are far from straightforward. For example the success of automated classification using per-point classifiers will be a balance between the importance of scene noise within classes and of the

frequency of boundary pixels between classes. With improving resolution, the number of boundary pixels will decline, but scene noise will increase: thus classification accuracies might be expected to improve and then worsen if a wide enough range of resolutions are considered for the same area.

There is a tendency for users to demand ever finer spatial resolution from satellite-derived data. Such wishes need to be militated by the fact that improved spatial resolution does not necessarily mean improved classification accuracy. In the future users of high resolution imagery may well degrade it initially before attempting classification, in order to achieve more accurate results. Moreover improvements in spatial resolution may result in the data flow reaching unmanageable proportions both for the agencies producing the data and for the user.

If the utility of satellite-derived data is to be better understood and if future satellite systems are to be designed more effectively, then further research is required in three areas. Firstly, resolution measures must be more closely linked to the quality and quantity of information which can be extracted from the data. Measures such as the effective resolution element represent a potentially important step in achieving this objective. Secondly information on the spatial properties of most terrain attributes needs to be significantly improved. Surprisingly Earth scientists have as yet largely failed to provide comprehensive quantitative data in a form which is compatible with estimating objective estimates of resolution requirements. Thirdly, results from these two research efforts must be integrated so that the benefits from improvements in resolution can be objectively assessed. Benefits from improved resolution need to be expressed in terms of the gains in accuracy and precision with which terrain attributes can be described: moreover ultimately the economic benefits from incremental improvements in resolution need to be determined.

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REFERENCES

- BAKER, L. R. and M. SCOTT 1975: Electro-optical remote sensors with related optical sensors. In Reeves, R. A., editor, *Manual of Remote Sensing*, Falls Church, Virginia: American Society of Photogrammetry.
- BLANCHARD, L. E. and O. WEINSTEIN 1980: Design challenges of the Thematic Mapper. *Institute of Electrical and Electronics Engineers transactions on geoscience and remote sensing* Ge-18, 146-160.
- BUCHTEMANN, W., 1974: MTF measurements and assessment of thermal imaging devices. *Proceedings of the Society of Photo-Optical Instrumentation Engineers* 46 (Image Assessment and Specification), 288-293.
- BYLANDER, E. A. 1979: *Electronic displays*. New York: McGraw-Hill.
- CAMPBELL, J. B., 1978: Spatial variation of sand content and pH within single contiguous delineations of two small mapping units. *Soil Science Society of America Journal* 42, 460-464.
- CLARK, J. and N. A. BRYANT 1977: Landsat-D thematic mapper simulation using aircraft multispectral data. *Proceedings 11th International Symposium on Remote Sensing of Environment*, Ann Arbor, Michigan, 483-491.
- COLVOCORESSES, A. P. 1979a: Proposed parameters for Mapsat. *Photogrammetric Engineering and Remote Sensing* 45, 501-506.
- CONVOCORESSES, A. P. 1979b: Effective resolution element (ERE) of remote sensors. *Memo-
randum for the record, Feb 8, 1979*. Reston, Virginia: United States Department of Interior, Geological Survey.
- CORBETT, F. J. 1974: Sensor performance evaluation of the Skylab multispectral photographic facility. *Proceedings of the Society of Photo-optical Instrumentation Engineers* 46 (Image assessment and specification), 239-246.
- CORSPERS (Committee on Remote Sensing Programs for Earth Resource Surveys) 1976: *Resource and environmental surveys from space with the thematic mapper in the 1980's*. Washington, D. C.: National Academy of Sciences.
- DOYLE, F. J. 1978: The next decade of satellite remote sensing. *Photogrammetric Engineering and Remote Sensing* 44, 155-164.
- DOYLE, F. J. 1979: A large format camera for shuttle. *Photogrammetric Engineering and Remote Sensing* 45, 73-78.

- EASTMAN, F. H. 1970: A high-resolution image sensor. *Journal of the Society of Motion Picture and Television Engineers* 79, 10-15.
- FORSHAW, M. R. B., A. HASKELL, P. F. MILLER, D. J. STANLEY, and J. R. G. TOWNSHEND 1980: *A review paper: Spatial resolution of remotely sensed imagery*. Paper submitted to U. S. Committee for Peaceful Uses of Outer Space (53 pages).
- FRASER, R. S. 1974: Computed atmospheric corrections for satellite data. *Proceedings of the Society of Photo-Optical Engineerings* 51 (Scanners and imagery; systems for Earth observation), 64-72.
- GAUBERT, A. M. 1978: SPOT: The French trial Earth observation system. *Proceedings of the 12th International Symposium on Remote Sensing of Environment* Ann Arbor, Michigan, 289-296.
- GENERAL ELECTRIC (undated): *Landsat 3 reference manual*. Valley Forge, Pennsylvania: General Electric.
- GENERAL ELECTRIC 1975: *Definition of the Total Earth resources system for the shuttle era. TOSS-TERSSE optional system study* 10. Valley Forge, Philadelphia: General Electric.
- GORDON, F. 1980: The space-time relationships of data-points (pixels) of the Thematic Mapper and the Multispectral Scanner or the "Myth of Simultaneity." *NASA Technical Paper* 1715. Goddard Space Flight Center, Greenbelt, Maryland: NASA.
- GURNEY, C. M. 1980: Threshold selection for line detection algorithms. *Institute of Electrical and Electronics Engineerings Transactions on Geoscience and Remote Sensing* GE-18, 204-211.
- HARALICK, R. M. 1979: Statistical and structural approaches to texture. *Proceedings of the Institute of Electrical and Electronics Engineers* 67, 786-804.
- HOLKENBRINK, P. E. 1978: *Manual on characteristics of Landsat computer-compatible tapes produced by the EROS data center digital image processing system*. Washington, D.C.: U.S. Department of Interior, Geological Survey.
- HOROWITZ, H. M., J. T. LEWIS and A. P. PENTLAND 1975: *Estimating proportions of objects from multispectral scanner data*. Ann Arbor, Michigan: Environmental Research Institute of Michigan, Report No. 109600-13-F.
- HORD, R. M. 1977: Digital enhancement of Landsat MSS data for mineral exploration. In Smith, W. L., editor, *Remote Sensing applications for mineral exploration*. Stroudsburg, Pennsylvania: Dowden, Hutchinson and Ross, 235-250.
- INTER AGENCY TASK FORCE 1979: *Integrated remote sensing systems* (NAS 5-23411). Washington, D. C.: General Electric.

- JET PROPULSION LABORATORY 1979: *Preliminary Stereosat Mission description*. Pasadena, California: NASA.
- JUSTICE, C. O. and J. R. G. TOWNSHEND 1979: Clear images from space. *Geographical Magazine* 51, 828-831.
- KAN, E. P., D. L. BALL, J. P. BASU, and R. L. SMELSER 1975: Data resolution versus forestry classification accuracy. *Symposium on machine processing of remotely sensed data*, Purdue University, Laboratory for Applications of Remote Sensing, 1B-24 to 1B-36.
- LANDGREBE, P. A., L. BIEHL and W. SIMMONS 1977: An empirical study of scanner system parameters. *Institute of Electrical and Electronic Engineers Transactions on Geoscience Electronics* GE-15, 120-30.
- LANSING, J. C. and R. W. CLINE 1975: The four and five band multispectral scanners for Landsat. *Optical Engineering* 14, 312-322.
- LAUER, D. T. and R. R. THAMAN 1971: Information content of simulated space photographs as a function of various levels of image resolution. *Proceedings of the 7th International Symposium on Remote Sensing of Environment*, Ann Arbor, Michigan 1191-1203.
- LAVIN, H. and M. QUICK 1974: The OTF in electro-optical imaging systems. *Proceedings of the Society of Photo-Optical Instrumentation Engineers*, 46 (Image assessment and specification), 279-286.
- LILLESAND, T. M. and R. W. KIEFER 1979: *Remote sensing and image interpretation*. New York: John Wiley and Sons.
- MCGILLEM, C. D., T. E. RIENER and, G. MOMBASSERI 1975: Resolution enhancement of ERTS imagery. *Symposium on machine processing of remotely sensed data*, Purdue University, West Lafayette, Indiana 3A-21 to 3A-29.
- MERIFIELD, P. M. and D. L. LAMAR 1975: Active and inactive faults in Southern California viewed from Skylab. *Proceedings NASA Earth resources survey symposium* 1B, Houston, Texas: NASA, 779-797.
- MITCHELL, C. W., R. WEBSTER, P. H. T. BECKETT and B. CLIFFORD 1979: An analysis of long-range predictions of conditions in deserts. *Geographical Journal* 145, 72-85.
- MOBASSERI, B. G., P. E. ANUTA, C. D. MCGILLEM 1980: A parameter model for multispectral scanners. *Institute of Electrical and Electronic Engineers Transactions on Geoscience and Remote Sensing*, GE-18, 175-179.
- MORGERNSTERN, J. P., R. E. NALEPKA, E. R. KENT, and J. ERICKSON 1976: *Investigation of Landsat follow-on thematic mapper spatial, radiometric and spectral resolution*. Ann Arbor, Michigan: Environmental Research Institute of Michigan, Report No. 119300-10-F.

- NALEPKA, R. F. and P. D. HYDE 1972: Classifying unresolved objects from simulated space data. *Proceedings 8th International Symposium on Remote Sensing of Environment*, Ann Arbor, Michigan, 935-949.
- NASA 1972: *Earth resources technology satellite. Data users handbook*. Goddard Space Flight Center, Greenbelt, Maryland: NASA.
- NASA 1973a: *Proceedings Symposium on Significant Results obtained from the Earth Resources Satellite*. Goddard Space Flight Center, Maryland: NASA.
- NASA 1973b: *Advanced scanners and imaging systems for Earth observations*. (NASA SP-335). U.S. Govt Printing Office, Washington, D. C.: NASA.
- NASA 1975: *Proceedings NASA Earth resources survey symposium*. (NASA TMX-58168), Houston, Texas: NASA.
- NASA 1980a: *Landsat data user's notes*, 12. U.S. Geological Survey, EROS Data Center, Sioux Falls, South Dakota: NASA.
- NASA 1980b: *NASA Activities*, 11 (6). Washington, D. C.: NASA.
- NORWOOD, V. T. 1974: Balance between resolution and signal-to-noise ratio in scanner design for Earth resources systems. *Proceedings Society of Photo-instrumentation Engineers* 51, 37-42.
- OTTERMAN, J. 1969: Diffraction-limited resolution for geoscience imagery. *Applied Optics* 9, 1887-1889.
- PERRIN, F. H. 1966: The structure of the developed image. In James, T. H., editor, *The theory of the photographic process*. New York: MacMillan, 499-551.
- PODWYSOCKI, M. H. 1976: *An estimate of field size distribution for selected sites in the major grain producing countries* (X-923-74-93). Goddard Space Flight Center, Greenbelt, Maryland: NASA.
- PODWYSOCKI, M. H., F. J. GUNTER, H. W. BLODGET and A. T. ANDERSON 1979: A comparison of rock discrimination capabilities based on present and future Landsat satellite sensor systems. *Proceedings 13th International Symposium on Remote Sensing of Environment*, Ann Arbor, Michigan, 79-80.
- RCA GOVERNMENT SYSTEM DIVISION 1977: *Return beam vidicon (RBV) panchromatic two-camera subsystem for Landsat-C. Final Report* (AE R-4231). Princeton, New Jersey: RCA Astro-electronics.

- SADOWSKI, F. A., W. A. MALILA, J. E. SARNO, and R. F. NALEPKA 1977: The influence of multispectral scanner resolution on forest feature classification. *Proceedings 11th International Symposium on Remote Sensing of Environment*, Ann Arbor, Michigan, 1279-1288.
- SADOWSKI, F. A., and J. SARNO 1976: *Forest classification accuracy as influenced by multi-spectral scanner spatial resolution*. Ann Arbor, Michigan: Environmental Research Institute Michigan, Report No. 109600-71F.
- SALOMONSON, V. V. 1978: Landsat-D: A systems overview. *Proceedings 12th International Symposium on Remote Sensing Environment*, Ann Arbor, Michigan, 371-385.
- SALOMONSON, V. V., P. L. SMITH, A. B. PARK, W. C. WEBB, and T. J. LYNCH 1980: An overview of progress in the design and implementation of Landsat-D systems. *Institute of Electrical and Electronic Engineers transactions on geoscience and remote sensing*, GE-18, 137-146.
- SCHINDLER, R. A. 1979: Physical measures of image quality and their relationship to performance. *Proceedings of the Society of Photo-Optical Instrumentation Engineers* 199, (Advances in display technology), 118-125.
- SCHOWENGERDT, R. A. 1976: A method for determining the operational imaging performance of Orbital Earth Resources Sensors. *Proceedings of the American Society of Photogrammetry* 42, 25-62.
- SCOTT, F. and G. C. BROCK 1973: Image structure and evaluation. In Thomas, W., editor, *Society of Photo-Science Engineers handbook of photographic science and engineering*, New York: John Wiley, 925-980.
- SHAW, R. 1979: Photographic detectors. In Shannon, R. R. and J. C. Wyant, editors, *Applied optics and optical engineering*, vol. VII, New York: Academic Press, 121-154.
- SHAY, R., A. POTTER, M. BAUER, R. BERSTEIN, R. HARALICK, A. KOSO, V. SALOMONSON 1975: Appendix F, Subgroup 2 Report. In Harnage, J. and D. Landgrebe, editors, *Landsat-D Thematic Mapper Technical working group final report* (JSC-09797). Houston, Texas: NASA.
- SLATER, P. N. 1975a: Photographic Systems for Remote Sensing. In Reeves, R. A., editor, *Manual of Remote Sensing*, Falls Church, Virginia: American Society of Photogrammetry, 235-321.
- SLATER, P. N. 1975b: Use of MTF in the specification and first-order design of electro-optical and photographic imaging and radiometric systems. *Optica Acta* 22, 277-290.
- SLATER, P. N. 1975c: Basic differences in the quality of analog and digital imagery from photographic and solid state array remote sensing systems. *Proceedings of the American Society of Photogrammetry*, 41, 139-153.

- SLATER, P. N. 1979: A re-examination of the Landsat MSS. *Photogrammetric Engineering and Remote Sensing*, 45, 1479-1485.
- SMITH, W. J. 1978: Optical design. In Wolfe, W. L. and G. J. Zizziz, editors, *The Infrared Handbook*, Washington, D. C.: Office of Naval Research, Department of the Navy.
- STEINER, D. and A. E. SALERNO 1975: Remote sensor data systems, processing and management. In Reeves, R. G., editor, *Manual of Remote Sensing*. Falls Church, Virginia: American Society of Photogrammetry, 611-803.
- STROME, W. M. 1979: Communication to A. P. Colvocoresses, reference 1372-113-2-2, February 19, 1979, Canada Centre for Remote Sensing.
- SWAIN, P. H. and S. M. DAVIS 1978: *Remote sensing: the quantitative approach*. New York: McGraw-Hill.
- SWAIN, P. H., B. J. SIEGEL and B. W. SMITH 1980: Contextual classification of multispectral remote sensing data using a multiprocessor system. *Institute of Electrical and Electronics Engineers Transactions in Geoscience and Remote Sensing* GE-18, 190-196.
- THOMPSON, L. L. 1979: Remote Sensing using solid state array technology, *Photogrammetric Engineering and Remote Sensing* 45, 47-55.
- THOMSON, F. J., J. D. ERICKSON, R. F. NALEPKA, and F. WEBER 1974: *Final report-multi-spectral scanner data applications evaluation. Vol. 1 User applications study*. Ann Arbor, Michigan: Environmental Research Institute Michigan, Rep. No. 102800-40-I.
- TOWNSHEND, J. R. G. 1981: Image analysis and interpretation for land resources survey. In Townshend, J. R. G., editor, *Terrain analysis and remote sensing*. London: George Allen and Unwin, (in press).
- TOWNSHEND, J. R. G. and C. O. JUSTICE 1979: The role of Landsat 3 RBV images for thematic mapping. *Proceedings 3rd International GDTA conference of Cartographic Processing and Analysis of Satellite Data*. Toulouse (in press).
- TOWNSHEND, J. R. G. and D. F. WILLIAMS and C. O. JUSTICE 1979: An evaluation of Landsat 3 RBV imagery for an area of complex terrain in southern Italy. *Proceedings 13th Symposium on Remote Sensing of Environment*, Ann Arbor, Michigan, 1839-1852.
- TUCKER, C. J. 1978: An evaluation of the first four Landsat D thematic mapper reflective sensors for monitoring vegetation: a comparison with other satellite sensor systems. *NASA Technical Memorandum*, 79617, Goddard Space Flight Center, Greenbelt, Maryland: NASA.
- TUCKER, C. J. 1979: Radiometric resolution for monitoring vegetation. How many bits are needed? *NASA Technical Memorandum* 80293, Goddard Space Flight Center, Greenbelt, Maryland: NASA.

- U. S. GEOLOGICAL SURVEY 1979: *Landsat data user's handbook*. (Revised edition.) Reston, Virginia: U.S. Department of Interior.
- WEBSTER, R. 1978: Mathematical treatment of soil information. *Proceedings 11th Congress International Society of Soil Science*, Edmonton, 3, 161-190.
- WEBSTER, R. and P. H. BECKETT 1970: Terrain classification and evaluation using air photography: A review of recent work at Oxford. *Photogrammetria* 26, 51-75.
- WELCH, R. 1971: Modulation transfer functions. *Photogrammetric engineering*, 37, 247-259.
- WELCH, R. 1972: The prediction of resolving power of air and space photographic systems. *Image Technology* 14, 25-32.
- WELCH, R. 1974: MTF analysis techniques applied to ERTS-1 and Skylab-2 imagery. *Proceedings of the Society of Photo-Optical Instrumentation Engineers* 46, (Image assessment and specification), 258-62.
- WELCH, R. 1977: Progress in the specification and analysis of image quality. *Photogrammetric Engineering and Remote Sensing* 43, 709-719.
- WIERSMA, D. J. and D. A. LANDGREBE 1978: The analytical design of spectral measurements for multispectral remote sensor systems. *LARS Technical Report* 122678, West Lafayette, Indiana: Laboratory for Applications of Remote Sensing.
- WIGHT, R. 1979: Sensor implications of high altitude low contrast imagery. *Photogrammetric Engineering and Remote Sensing* 45, 63-66.